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## TRANSMITTAL LETTER TO THE UNITED STATES

032/02161

DESIGNATED/ELECTED OFFICE (DO/EO/US)

U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR

CONCERNING A FILING UNDER 35 U.S.C. 371

09/856761

INTERNATIONAL APPLICATION NO.

INTERNATIONAL FILING DATE

PRIORITY DATE CLAIMED

PCT/99/00639

November 26, 1999

November 27, 1998

TITLE OF INVENTION

A METHOD FOR FORMING A PERSPECTIVE RENDERING FROM A VOXEL SPACE

APPLICANT(S) FOR DO/EO/US

Shmuel AKERMAN; Gad MILLER

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371 (c) (2))
  - a. ☒ is transmitted herewith (required only if not transmitted by the International Bureau).
  - b. ☒ has been transmitted by the International Bureau.
  - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☒ A copy of the International Search Report (PCT/ISA/210).
8. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3))
  - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
  - b. ☐ have been transmitted by the International Bureau.
  - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
  - d. ☐ have not been made and will not be made.
9. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
10. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).
11. ☒ A copy of the International Preliminary Examination Report (PCT/IPEA/409).
12. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).

## Items 13 to 18 below concern document(s) or information included:

13. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
14. ☒ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
15. ☒ A **FIRST** preliminary amendment.  
A **SECOND** or **SUBSEQUENT** preliminary amendment.
16. ☐ A substitute specification.
17. ☐ A change of power of attorney and/or address letter.
18. ☐ Certificate of Mailing by Express Mail
19. ☒ Other items or information:

Amendments to the claims of the International Application under PCT Article 34 are transmitted herewith as annexes to the IPER.

U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.53) <b>09/856761</b>	INTERNATIONAL APPLICATION NO. <b>PCT/IL99/00639</b>	ATTORNEY'S DOCKET NUMBER <b>032/02161</b>
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20. The following fees are submitted:

**BASIC NATIONAL FEE ( 37 CFR 1.492 (a) (1) - (5)) :**

- ☒ Search Report has been prepared by the EPO or JPO ..... **\$860.00**  
~~\$930.00~~
- ☐ International preliminary examination fee paid to USPTO (37 CFR 1.482) ..... **\$720.00**
- ☐ No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2)) ..... **\$790.00**
- ☐ Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... **\$1,070.00**
- ☐ International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) ..... **\$98.00**

**ENTER APPROPRIATE BASIC FEE AMOUNT =****CALCULATIONS PTO USE ONLY**Surcharge of **\$130.00** for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).**\$860.00****\$0.00**

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE
Total claims	49 - 20 =	29	x \$18.00
Independent claims	1 - 3 =	0	x \$80.00
Multiple Dependent Claims (check if applicable).			<input type="checkbox"/>

**\$522.00****\$0.00****\$0.00****TOTAL OF ABOVE CALCULATIONS =****\$1,382.00**

Reduction of 1/2 for filing by small entity, if applicable. Verified Small Entity Statement must also be filed (Note 37 CFR 1.9, 1.27, 1.28) (check if applicable).

☒**\$691.00****SUBTOTAL =****\$691.00**Processing fee of **\$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (f)).**\$0.00****TOTAL NATIONAL FEE =****\$691.00**

Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) (check if applicable).

☐**\$0.00****TOTAL FEES ENCLOSED =****\$691.00**Amount to be:  
refunded

\$

charged

\$

- ☐ A check in the amount of \_\_\_\_\_ to cover the above fees is enclosed.
- ☒ Please charge my Deposit Account No. **03-3419** in the amount of **\$691.00** to cover the above fees.  
A duplicate copy of this sheet is enclosed.
- ☒ The Commissioner is hereby authorized to charge any fees which may be required, or credit any overpayment to Deposit Account No. **03-3419** A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

William H. Dippert, Esq.  
Cowan, Liebowitz & Latman, P.C.  
1133 Avenue of the Americas  
New York, NY 10036-6799  
USA

Tel.: (212) 790-9200

*Paul Fenster*  
SIGNATURE

Paul FENSTER

NAME

33,877

REGISTRATION NUMBER

May 21, 2001

DATE

## IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant: S. AKERMAN et al.  
Serial Number: Not yet assigned  
Filed: 26 November 1999 as PCT/IL99/00639 and herewith as U.S. National  
Stage  
For: A Method for Forming a Perspective Rendering from Voxel Space  
Art Unit: Not yet assigned

Honorable Commissioner of Patents and Trademarks  
Washington DC 20231

**PRELIMINARY AMENDMENT**

Sir:

Further to the concurrent filing of a U.S. national stage application of PCT Application No. PCT/IL99/00639, kindly amend the application as follows:

**IN THE SPECIFICATION**

Kindly add the following section on page 1, immediately after the title

**--RELATED APPLICATION**

This application is a U.S. national filing of PCT Application No. PCT/IL99/00639, filed November 26, 1999, the disclosure of which is incorporated herein by reference.--

**IN THE CLAIMS**

Kindly replace the present claims 6, 8, 12-14, 18-19, 22-24, 27-29, 32-33, 35-42, 45-49 with the following claims in clean form:

6. (Amended) A method according to claim 1, comprising calculating said boundary visualization value during said ray casting.
8. (Amended) A method according to claim 1, comprising:  
providing an index array indicating for at least some of said voxels if a class-boundary does not pass near the voxel.
12. (Amended) A method according to claim 1, wherein said associated boundary visualization value comprises a surface lighting calculation of said boundary.

13. (Amended) A method according to claim 1, comprising stopping said ray casting if said accumulated opacity is over a threshold.
14. (Amended) A method according to claim 1, wherein said sampling points are separated by a step size and wherein said step size is dependent on the opacity value at the sampling points.
18. (Amended) A method according to claim 1, comprising providing a definition of voxel value intervals for each class, prior to said ray casting.
19. (Amended) A method according to claim 1, comprising:  
interpolating between voxels near said point; and  
transforming said interpolated voxel value into an opacity value for said point.
22. (Amended) A method according to claim 1, wherein said predetermining location is within the voxel space.
23. (Amended) A method according to claim 1, wherein said voxel data set comprises a medical imaging data set.
24. (Amended) A method according to claim 1, wherein (g) comprises:  
sparely casting rays; and  
determining if to cast at least one additional ray between cast rays.
27. (Amended) A method according to claim 25, wherein statistical homogeneity is determined with respect to depth factors associated with the ray.
28. (Amended) A method according to claim 1, wherein (h) comprises interpolating between stored values of cast rays.
29. (Amended) A method according to claim 1, wherein (g) comprises progressively increasing the density of raycasting.

32. (Amended) A method according to claim 1, comprising rendering said formed perspective rendering on a display.

33. (Amended) A method according to claim 1, comprising defining a window in or near the voxel space through which to cast said rays.

35. (Amended) A method according to claim 33, wherein said window is flat and rectangular.

36. (Amended) A method according to claim 33, wherein said window is curved.

37. (Amended) A method according to claim 33, wherein said window is defined by pixels in a uniformly spaced rectangular grid.

38. (Amended) A method according to claim 33, wherein said window is defined by pixels using coordinates which are one of circular coordinates, elliptical coordinates and another conic projection of coordinates.

39. (Amended) A method according to claim 1, wherein said accumulation of opacity comprises updating a storage value CT as follows:  $CT = CT * T^{\text{step\_size}}$ , where T is a transparency value corresponding to the opacity value.

40. (Amended) A method according to claim 1, wherein said rays are cast in parallel.

41. (Amended) A method according to claim 1, wherein the voxel data set is generated by one of CT (Computerized Tomography), MRI (Magnetic Resonance Imaging), Ultrasound, a geophysical survey, a meteorological survey, a scientific simulation, an animation model having more than two dimensions and a set of simultaneous equations.

42. (Amended) A method according to claim 1, wherein each voxel has associated therewith a visual representation value and comprising:

determining a visualization value associated with a sampled point from the voxel associated visual representation values; and

accumulating said point associated visualization value into said stored value.

45. (Amended) A method according to claim 42, wherein accumulating said point associated visualization values comprises selectively accumulating values based on front surface detection.

46. (Amended) A method according to claim 42, wherein said point associated visualization value comprises a volume lighting value.

47. (Amended) A method according to claim 42, wherein said point associated visualization value comprises a surface lighting value.

48. (Amended) A method according to claim 1, wherein advancing along a ray is coordinated with an opacification process.

49. (Amended) Apparatus for forming a perspective rendering from a voxel space including:

(a) a memory for storing a voxel data set;

(b) a computer processor for applying the method of claim 1 to said stored data set to form said perspective rendering; and

(c) a second memory for storing said formed perspective rendering.

**REMARKS**

The present application is a U.S. national application of PCT Application No. PCT/IL99/00639 filed November 26, 1999. The claims in the present application were amended by limiting the number of claims and removing multiple dependencies, to reduce costs and put them in better form for examination in the US.

Applicants wish to bring to the attention of the Examiner that the claims in the present application are based on those attached to the International Preliminary Examination Report dated February 26, 2001 issued by the European Patent Office (acting as IPEA).

Attached is a marked up set of the amended claims.

An examination on the merits is respectfully requested.

Respectfully submitted,  
S. AKERMAN et al.

*Paul Fenster*

Paul Fenster  
Reg. No. 33,877

May 21, 2001  
William H. Dippert, Esq.  
Cowan, Liebowitz and Latman, P.C.  
1133 Avenue of the Americas  
New York, NY 10036-6799

Tel: (212) 790-9200

## Version with Markings to Show Changes Made

6. (Amended) A method according to claim 1 ~~any of claims 1-5~~, comprising calculating said boundary visualization value during said ray casting.

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8. (Amended) A method according to claim 1 ~~any of claims 1-6~~, comprising:  
providing an index array indicating for at least some of said voxels if a class-boundary does not pass near the voxel.

10 12. (Amended) A method according to claim 1 ~~any of claims 1-11~~, wherein said associated boundary visualization value comprises a surface lighting calculation of said boundary.

13. (Amended) A method according to claim 1 ~~any of claims 1-12~~, comprising stopping said ray casting if said accumulated opacity is over a threshold.

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14. (Amended) A method according to claim 1 ~~any of claims 1-13~~, wherein said sampling points are separated by a step size and wherein said step size is dependent on the opacity value at the sampling points.

20 18. (Amended) A method according to claim 1 ~~any of claims 1-17~~, comprising providing a definition of voxel value intervals for each class, prior to said ray casting.

19. (Amended) A method according to claim 1 ~~any of claims 1-18~~, comprising:

interpolating between voxels near said point; and

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transforming said interpolated voxel value into an opacity value for said point.

22. (Amended) A method according to claim 1 ~~any of claims 1-21~~, wherein said predetermining location is within the voxel space.

30 23. (Amended) A method according to claim 1 ~~any of claims 1-22~~, wherein said voxel data set comprises a medical imaging data set.



24. (Amended) A method according to claim 1~~any of claims 1-23~~, wherein (g) comprises:  
 sparsely casting rays; and  
 determining if to cast at least one additional ray between cast rays.

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27. (Amended) A method according to claim 25~~or claim 26~~, wherein statistical homogeneity is determined with respect to depth factors associated with the ray.

28. (Amended) A method according to claim 1~~any of claims 1-27~~, wherein (h) comprises  
 10 interpolating between stored values of cast rays.

29. (Amended) A method according to claim 1~~any of claims 1-27~~, wherein (g) comprises progressively increasing the density of raycasting.

15 32. (Amended) A method according to claim 1~~any of claims 1-31~~, comprising rendering said formed perspective rendering on a display.

33. (Amended) A method according to claim 1~~any of claims 1-32~~, comprising defining a window in or near the voxel space through which to cast said rays.

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35. (Amended) A method according to claim 33~~or claim 34~~, wherein said window is flat and rectangular.

36. (Amended) A method according to claim 33~~or claim 34~~, wherein said window is curved.

25

37. (Amended) A method according to claim 33~~claim 33-36~~, wherein said window is defined by pixels in a uniformly spaced rectangular grid.

38. (Amended) A method according to claim 33~~claim 33-36~~, wherein said window is defined  
 30 by pixels using coordinates which are one of circular coordinates, elliptical coordinates and another conic projection of coordinates.

39. (Amended) A method according to claim 1~~any of claims 1-38~~, wherein said accumulation of opacity comprises updating a storage value CT as follows:  $CT = CT * T^{\text{step\_size}}$ , where T is a transparency value corresponding to the opacity value.

40. (Amended) A method according to claim 1~~any of claims 1-39~~, wherein said rays are cast in parallel.

41. (Amended) A method according to claim 1~~any of claims 1-40~~, wherein the voxel data set is generated by one of CT (Computerized Tomography), MRI (Magnetic Resonance Imaging), Ultrasound, a geophysical survey, a meteorological survey, a scientific simulation, an animation model having more than two dimensions and a set of simultaneous equations.

42. (Amended) A method according to claim 1~~any of claims 1-41~~, wherein each voxel has associated therewith a visual representation value and comprising:

determining a visualization value associated with a sampled point from the voxel associated visual representation values; and  
accumulating said point associated visualization value into said stored value.

45. (Amended) A method according to claim 42~~any of claims 42-44~~, wherein accumulating said point associated visualization values comprises selectively accumulating values based on front surface detection.

46. (Amended) A method according to claim 42~~any of claims 42-45~~, wherein said point associated visualization value comprises a volume lighting value.

47. (Amended) A method according to claim 42~~any of claims 42-46~~, wherein said point associated visualization value comprises a surface lighting value.

48. (Amended) A method according to claim 1~~any of claims 1-47~~, wherein advancing along a ray is coordinated with an opacification process.

49. (Amended) Apparatus for forming a perspective rendering from a voxel space including:

(a) a memory for storing a voxel data set;

(b) a computer processor for applying the method of claim 1 ~~any of the claims 1-48~~ to

5 said stored data set to form said perspective rendering; and

(c) a second memory for storing said formed perspective rendering.

A Method for Forming A Perspective Rendering from A Voxel Space**FIELD OF THE INVENTION**

This invention relates to a method for forming a perspective rendering from a space of volume elements (voxels). More specifically, this invention relates to a family of algorithmic optimizations, which are useful in the  
5 forming of a perspective rendering from a voxel space.

**BACKGROUND OF THE INVENTION**

Many quantitative disciplines collect or generate multidimensional data. These disciplines include medical imaging applications such as CT or  
10 MRI; geophysical modeling, meteorological forecasting, scientific simulations, animation models, and the like. This multidimensional data is often stored and manipulated in the form of voxels. Voxels are volume elements in three (or more) dimensions; and are analogous to pixels (two dimensional picture elements).

15 Professionals often find it useful to be able to visualize some aspect of voxel data. The visualization requires transforming the voxel data, so that a cross-section, a projection, or another form of visualization can be realized on a two-dimensional display device. Numerous visualization techniques have been explored, and most are unfeasible for application; by reason of

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computational complexities associated therewith. Nevertheless, there are certain basic desirable aspects of visualization standards for accepted renderings (representations).

The professional expects the visualization to facilitate elevated insights  
5 and to evoke increased understanding of the data. This is often accomplished by imposing (onto a rendering of the data) subjective criteria such as depth, shading, perspective, lighting, or shadowing; which are not necessarily generic to the data being rendered. For example, depth or shadow are not natural features of geophysical cross-sections; but may be helpful to the  
10 professional who is looking for ways to understand such a complex data set. Alternately, the professional may expect the visualization to be life-like (of realistic appearance).

The result of the professionals' rendering expectations and the computational complexity of accomplishing them has generated a cluttered  
15 convolution of rendering techniques. Some techniques have been developed which are specific to rendering certain data sets, while other techniques are seemingly more general in scope.

The nature of the prior art (of rendering a voxel space) can be better appreciated from studying US5201035, US5499323, US5594844, and from  
20 the prior art references cited therein. Furthermore, the order of complexity required for successful algorithmic optimization, in forming a perspective rendering from a voxel space, will thereby be appreciated.

The prior art is problematic and primarily application specific. Many overlapping combinations of more fundamental graphics algorithms are used  
25 in an attempt to simultaneously provide adequate rendering within algorithmic bounds that are economically and technically practical. Many examples of prior art methods are visually realistic but algorithmically heavy, and many other examples of the prior art are visually simplistic albeit

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algorithmically feasible. Thus, there is a need in the art for rendering methods that are simultaneously visually realistic and algorithmically practical.

## SUMMARY OF THE INVENTION

5       The present invention relates to a method for forming a high spatial resolution perspective rendering from a low spatial resolution voxel space, the method including the steps of: (a) **initializing** a virtual window of predetermined resolution pixels, and placing the virtual window in or near the voxel space; (b) from a predetermined vantage-point, sparsely **ray-casting** a  
10   plurality of vectors through the virtual window into the voxel space; (c) **calculating** a visualization-value for each ray-cast vector not having an associated visualization-value, and therein for each position in a step dependent series of positions on the vector, and in a position ordering of steps from the vantage-point through the pixel, until an accumulated  
15   transparency-value threshold is reached or until a last available voxel intersecting with the vector is reached - whichever is sooner; by: *FIRSTLY interpolating* values of proximate voxels into an interpolated voxel value for the position; *SECONDLY transforming* the interpolated voxel value into a derived visualization-value and transparency value; and *THIRDLY*, using a  
20   predetermined selection rule, **accumulating** the derived visualization-value with a value presently stored in the corresponding pixel; and (d) until every pixel has an associated visualization-value, **selecting** a pixel (P) not yet having a visualization value, and *IF* substantially nearest pixels to the selected pixel (P) have computed visualization-values that are statistically  
25   homogenous, *THEN interpolating* a visualization-value from these substantially nearest pixels, and **assigning** the interpolated visualization-value to the selected pixel (P), *ELSE* ray-casting a vector

through the selected pixel (P) and assigning a visualization-value to the selected pixel (P) using *step (c)*.

The present invention provides a feasible method, both visually and algorithmically, for forming a high spatial resolution image perspective  
5 volume rendering from a low spatial resolution voxel space. The data, to be rendered into a visualization, is represented in a three-dimensional array of volume elements (voxels). Since the data stored in the voxels is not necessarily of a format, magnitude, or distribution useful for representation (e.g. on a display device such as a TV screen, a plotter, or the like), a  
10 transformation step is required in order to conform the data to a form that may be presented on a display device. These classes are used to transform one or more ranges of voxel values to doublets of a transparency-value and a representation-value (e.g. RGB for color, or gray-level, or the like). Recall that transparency-value and opacity-value are inverse quantifications of the  
15 same visualization aspect, so it is only by convenience of conceptualization that the present invention is described according to transparency-values or opacity-value.

According to the present invention, some interpolations are done before voxel value to visualization value transformations while other  
20 interpolations are done after these transformations. Interpolation is one of the key tools used to render a high-resolution image from a lower resolution representation. There are many functions that have proven useful for performing interpolations. Interpolation computationally solves for a value at a selected position from two or more neighboring positions. Interpolation  
25 functions may even consider all known locations having data-values to solve for a single location whose data-value is sought. In general, interpolation functions can be ordered; either in the same sense as polynomials, or according to a measure of algorithmic-computational complexity.

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The tradeoff between low-order interpolations (e.g. linear), intermediate-order interpolations (e.g. cubic or spline), and higher-order interpolations directly affects the visual smoothness of appearance for images wherein interpolations have been used to synthetically create values for  
5 locations where no such values existed in the original data. Even for intermediate-order interpolations, there is a large algorithmic expense.

Therefore, in visualization applications, normally low-order interpolations are used for solving at all interpolation-requiring positions, except for a most critical sub-set of positions, such as positions close enough  
10 to the eye (e.g. foreground objects and not backgrounds). Furthermore, switching between different order interpolations is noticeable, and requires some secondary compensatory mechanism - especially if the criterion is proximity to the eye. These special considerations, for preserving an appearance of smoothness, are especially important because - often an object  
15 of the visualization is to maintain the clear resolution of distinct class boundaries (in the form of continuous iso-surfaces of voxel-values - as explained below).

In the context of the present invention:

- (i) An "iso-surface" is a manifold in space in which the interpolation function  
20 of the voxel values is constant.
- (ii) A "class" is the region in space in which the interpolation function assumes values that belong to a predefined interval.

Therefore, by the continuity of the interpolation function, it follows that a class is bounded by the iso-surface(s) corresponding to the edge(s) of the  
25 class(s) interval. It should be appreciated that in the context of the present invention the iso-surfaces that are "interesting" with respect to processing are the class bounding iso-surfaces.

Another significant aspect in rendering a visualization of data relates to lighting. There are two basic types of lighting: surface lighting and volume

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- lighting. Surface lighting occurs (is desired) when an external light source illuminates the surfaces of the classes. In the context of the preferred embodiment of the present invention, surface lighting originates from the same predetermined vantage-point as the "eye of the observer". By contrast,
- 5 volume lighting derives from (is desired when) one or more voxels, in the "voxel space", are of themselves sources of illumination (radiant). In the context of several embodiments of the present invention, either surface lighting is used exclusively or volume lighting is used to complement surface lighting. According to one embodiment of the present invention, volume
- 10 lighting is used exclusively.

Qualitatively, surface lighting values are proportional to the cosine of the angle formed between a vector connecting the eye and a point on an iso-surface and a normal to the iso-surface at that point; according to the embodiment where the light source is coterminous with the eye.

- 15 Qualitatively, volume lighting is proportional to the luminance (radiance) associated with one or more points in the voxel space, the distance between the luminescent point and the vantage-point (the eye), and the opacity (or equivalently but inversely - the transparency) of relevant voxels between the luminescent point and the vantage-point (the eye).

- 20 Qualitatively, opacity accumulates differently (between each voxel and the eye) according to the lighting model: surface, volume, or combination. In general, cumulative opacity represents the "Fraction of Light" ("FoL") (also referred to as "CT" - Cumulative Transparency) reaching the eye from a point in the voxel space; due to the light absorptive nature of the medium between
- 25 the two (the eye and the point). Furthermore, it should be noted that the spatial precision necessary for successful rendering of surface lighting is significantly higher than that required for successful volume lighting.

According to the volume lighting model, luminescence (radiance) of the point is scaled (attenuated) by FoL by the time it reaches the eye.

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According to the surface lighting model, luminescence (radiance) of the eye is scaled (attenuated) by  $FoL * FoL$  by the time it completes the path of from the eye to point and back to the eye. Furthermore, the surface normal direction used in the surface lighting calculation for iso-surfaces is determined using  
5 any one of many well-known analytic estimates for a gradient (of the interpolated iso-surface).

Accumulating a transparency value into a pixel is by updating the present transparency value for the pixel:  $CT^* = T^{\text{current step size}}$  (see Figure 5); the present transparency value for the position on the vector exponentiated  
10 by the distance on the vector from the present position to the last position accumulated into the pixel; and the present transparency value for the position on the vector is a unit normalized transparency value.

A further significant aspect in "the process of volume rendering a  
15 visualization of data" relates to a well-known general technique called "ray-casting". Ray-casting substantially simulates a plurality of optical-information vectors that converge at the focal point of the eye. Equivalently, ray-casting simulates an algorithmic process wherein an accumulation of optical-information is organized with respect to a plurality of  
20 coterminous vectors; emanating outward from the eye. This algorithmic process enables a truncation of the vector (the cast ray) when the cumulative transparency of the traversed path becomes negligible.

According to the present invention, positions along the vector are selected for accumulating transparency values, and the step size between a  
25 present position and a next position is selected to be dependent on the opacity at the present position; albeit minimal and maximal step sizes limit the bounds of this proportionality. Furthermore, a change of class is detected by noting a change in opacity between two consecutive steps on a vector. Furthermore, according to the preferred embodiment of the present invention, in a region

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traversed by the vector having a high transparency the step size is large and in a region traversed by the vector having a low transparency the step size is small.

According to the preferred embodiment of the present invention,  
5 volume lighting contributions are produced everywhere, whereas surface lighting contributions are only produced when crossing from a class of lower opacity to a class of higher opacity. This crossing is at a surface that is facing the eye (a front surface), while a crossing from higher to lower classes of opacity is a "hidden" surface (a back surface). For example, in a medical data  
10 context if a vector traverses through a mucus and encounters a tissue, then this encounter is a front surface; while the continuation of the vector may pass again into a mucus and this "second passing" is a back surface.

According to the criteria (for interpolation) for preserving an appearance of smoothness in the rendering of continuous iso-surfaces, a high  
15 order of spatial precision is necessary whenever a front surface's surface lighting contribution (to the cumulative opacity of the ray-cast vector) is to be calculated. Therefore, according to the preferred embodiment of the present invention, whenever a front surface is detected between two consecutive steps – a smaller step-size search is performed between the two "consecutive  
20 steps". This search is in order to achieve a higher order of spatial positioning for a point on the front surface intersecting with the vector; and also for the normal to this point on the iso-surface.

Given the special significance of these front surfaces to the rendering process, an additional layer of processing is introduced. This processing is  
25 intended to substantially prevent a situation from occurring wherein two consecutive steps skip over a front surface without detecting it. Continuing in the medical context example, suppose there is a membrane (or thin film of tissue or a bone fragment, etc) in the mucus, that is tangential to the vector. Because the membrane is surrounded by a transparent substance, the step size

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risks "jumping over" the membrane without detecting the existence of the membrane.

Therefore according to the preferred embodiment of the present invention, an opacity-perturbation operation ("opacification") is performed.

- 5 This opacification process is intended to prevent jumping over front surfaces without detecting their presence. In the opacification process, a table (or equation) is prepared from which an opacity value can be assigned to each voxel value. According to this table (or equation), opacity for each voxel value is taken as the maximum value of a predetermined neighborhood with
- 10 respect to the original voxel value. Furthermore, step size on the vector is according to this table. Because this table effectively flags regions wherein there may be a front surface, the step size on the vector is always reduced whenever the vector is passing in the region of a front surface; even if there is no actual intersection between them. The perturbed values from the table (or
- 15 equation) are NOT used in the accumulation of a cumulative opacity; and are only used as a conservative strategy for properly optimizing (better choosing of appropriate) step sizes so as to achieve a visually acceptable rendering.

- According to the present invention, another aspect in the process of volume rendering relates to selective ray-casting. As can be appreciated from
- 20 the forgoing aspects of processes involved in volume rendering, each actual vector that is cast (from the eye), and by virtue of which opacity data is accumulated, causes a measure of algorithmic complexity to be added into the cost of a volume rendering. Furthermore, it should be appreciated that an object of the present invention is to produce a high spatial resolution
- 25 perspective rendering from a low spatial resolution voxel space.

Recalling that the central tradeoff in volume rendering is to provide a feasible method (both visually and algorithmically), the preferred embodiment of the present invention is directed to minimizing the extent to which actual

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ray-casting is performed. According to a first approximation of this minimizing of ray-casting, a predetermined plurality of rays are cast.

According to one embodiment of the present invention, this predetermined plurality is distributed in a symmetric regular dispersion such  
5 that values for all intermediary rays can be interpolated from the cast rays without any additional ray-casting.

According to another embodiment of the present invention, intermediary rays are cast whenever the accumulated values from the heretofore cast rays are not statistically homogenous, and are otherwise  
10 interpolated.

According to a variation embodiment of the present invention, a first plurality of regularly distributed rays are cast; and in each region between these regularly cast rays a statistical homogeneity metric is computed. From these cast rays - *EITHER* values in the region are interpolated from  
15 neighboring cast-rays' values *OR* a next plurality of regularly distributed rays are cast in the region, and a next resolution metric is computed. This either-or processing is repeated *UNTIL* values for all rays in a desired spatial resolution of rays have associated values. This variation embodiment is an iterative zoom-in value filling process that uses, as appropriate, the previous  
20 embodiments of the present invention.

In general, the present invention can be defined as "A method for forming a high spatial resolution perspective rendering from a low spatial resolution voxel space". This method includes the four steps ("a" through  
25 "d") of:

(a) **initializing** a virtual window of predetermined resolution pixels, and placing the virtual window in or near the voxel space;

(b) from a predetermined vantage-point, sparsely ray-casting a plurality of vectors through the virtual window into the voxel space;

5 (c) (i) for each ray-cast vector not heretofore having an associated visualization-value,

(ii) and therein for each position in a step dependent series of positions on the vector,

10 (iii) and therein in a position ordering of from the vantage-point through the pixel,

(iv) and therein until an accumulated transparency-value threshold is reached or until a last available voxel intersecting  
15 with the vector is reached - whichever is sooner;

calculating a visualization-value and storing this visualization-value into the vector's corresponding pixel; by:

20 *FIRSTLY interpolating* values of proximate voxels into a interpolated voxel value for the position;

*SECONDLY transforming* the interpolated voxel value into a derived visualization-value and transparency value; and

25 *THIRDLY*, using a predetermined selection rule, *accumulating* the derived visualization-value with the value presently in the corresponding pixel; and

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- (d) until every pixel has an associated visualization-value, selecting a pixel (P) having the initialization from *step (a)*, and

5            *IF* substantially nearest pixels to the selected pixel (P) have computed visualization-values that are statistically homogenous,

10            *THEN* interpolating a visualization-value from these substantially nearest pixels, and assigning the interpolated visualization-value to the selected pixel (P),

15            *ELSE* ray-casting a vector through the selected pixel (P) and assigning a visualization-value to the selected pixel (P) using *step (c)*.

In relation to these four steps ("a" through "d" - above) and to the conditions and sub-steps therein, a few summary observations are worthy of note.

20            In step (a), according to the preferred embodiment of the present invention, the spatial resolution of the pixels is higher than that of a cross-section of voxels in the voxel space.

25            In step (b), if the vantage-point is far from the virtual window, then the rays cast through the virtual window will effectively be parallel each to another. Alternately, if the vantage-point is close to the virtual window, then the rays cast will effectively be approximating a divergent perspective; as subtended through the angle defined by the virtual window.

            In step (c), all four conditions must be satisfied in order for the "calculating and storing" operation to be performed.

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In step (c) condition (i), note that vectors are cast in step (b) and also in step (d) (at the “*ELSE*” sub-step).

In step (c) condition (ii), the "calculating and storing" are independently done for each position on the vector.

5        In step (c) condition (iii), there are two possible orderings in ray-casting. These orderings depend on whether the virtual window is between the voxel space and the vantage-point (as is the case for the present description); or equivalently whether the voxel space is between the vantage-point and the virtual window. The expression of "from the  
10 vantage-point through the pixel" is a convenient choice of nomenclature, which is not intended to exclude any equivalent logically consistent ordering. For example, if the virtual window were to be placed in the midst of the voxel space or if the vantage-point were to be placed in the midst of the voxel space, then there would be optional orderings such as:

- 15
- From the vantage-point to the virtual window.
  - From the vantage-point through the virtual window.
  - From the virtual window away from the vantage-point.
  - From the virtual window to (or through) the vantage-point.
  - From the end of the voxel space to the virtual window.
- 20
- From the end of the voxel space to the virtual window; and thereafter to (or through) the vantage-point.

In step (c) condition (iv), "whichever is sooner" relates to accumulating transparency until further accumulation will not effect the visualization or until there is no further data to effect the visualization.

25 Furthermore, "transparency threshold" is a lower bound (or if stated equivalently - to an opacity threshold that is an upper bound).

In step (c) "FIRSTLY", there are numerous methods for accomplishing the interpolation.



In step (c) "SECONDLY", the transforming is according to the representation that is desired on a display device. Should the transforming be for interfacing with further image processing, then the transforming is according to the values appropriate to that processing.

- 5 In step (c) "THIRDLY", the accumulating is according to a lighting model, such as the surface lighting model, the volume lighting model, a combination of these two lighting models, a lighting model wherein the illumination source is not coterminous with the eye, or the like.

- 10 In step (d), it should be recognized that if the sparse ray-casting of step (b) is sufficient (as might be the case when implemented using parallel processing on the order of a processor per cast ray), then the supplemental ray-casting of the "ELSE" sub-step may never occur. This is not particularly problematic given the visual and algorithmic considerations motivating the method of the present invention.

- 15 It should also be appreciated that when there is a regular distribution of cast rays through the virtual window (in step (d) or even if done directly from step (b)) and when this distribution describes a spatial resolution in the virtual window that is higher than the spatial resolution of a cross section of the voxel space, then step (d) is expected to reduce to "selecting" and  
20 "interpolating" substantially without any further "ray-casting".

## BRIEF DESCRIPTION OF THE DRAWINGS

- In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in  
25 which:

Figure 1 is a schematic diagram of ray-casting geometry;

Figure 2 is a schematic mapping of a ray-casting ordering on a virtual window;

- Figure 3 is a schematic diagram of a search on a ray for an iso-surface;  
Figure 4 is a schematic diagram of a ray cast near an opacified iso-surface;  
Figure 5 is a flowchart summarizing the basic logic process of the present method; and
- 5 Figure 6 is a schematic diagram of a computer system for forming a perspective rendering from a voxel space.

### DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

The present invention relates to a method for forming a high spatial  
10 resolution perspective rendering from a low spatial resolution voxel space.  
(Turning to Figure 1, which is a schematic diagram of ray-casting geometry.  
This geometry is a typical geometry that is used in many embodiments of the  
present invention.) The method includes the four steps of:

- 15 (a) **Initializing** a virtual window (1) of predetermined resolution pixels (2) (3), and placing the virtual window in or near the voxel space (4). These pixels are logical storage elements corresponding to coordinates or regions of the virtual window. Normally, there is a simple and direct transformation from the geometry of the pixels  
20 of the virtual window to a display device (e.g. CRT, LCD, plotter, etc.).
- (b) From a predetermined vantage-point (5), sparsely **ray-casting** a plurality of vectors (6) (7) through the virtual window into the  
25 voxel space. (Turning to Figure 2, which is a schematic mapping of a ray-casting ordering on a virtual window. For example first casting rays through the pixels marked "X", then casting rays

through the pixels marked "O", and finally casting rays or interpolating for the unmarked pixels – as in step (d) below.)

5 (c) (Turning now to Figure 3, which is a schematic diagram of a search on a ray for an iso-surface) For each ray-cast vector not heretofore having an associated visualization-value, and therein for each position in a step dependent series of positions on the vector (for example (8) (9) (10)), and therein in a position ordering of from the vantage-point through the pixel, and therein until an  
10 accumulated transparency-value threshold is reached or until a last available voxel intersecting with the vector is reached - whichever is sooner; **calculating** a visualization-value **and storing** this visualization-value into the vector's corresponding pixel; by: *FIRSTLY interpolating* values of proximate voxels into an  
15 interpolated voxel value for the position (for example from voxels in the neighborhood of position (10) on the vector); *SECONDLY transforming* the interpolated voxel value into a derived visualization-value and transparency value; and *THIRDLY*, using a predetermined selection rule, *accumulating* the derived  
20 visualization-value with the value presently in the corresponding pixel.

(d) Until every pixel has an associated visualization-value, selecting a pixel (P) having the initialization from *step (a)*, and *IF*  
25 substantially nearest pixels to the selected pixel (P) have computed visualization-values that are statistically homogenous, *THEN interpolating* a visualization-value from these substantially nearest pixels, and *assigning* the interpolated visualization-value to the selected pixel (P), *ELSE* ray-casting a vector through the selected

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- pixel (P) and **assigning** a visualization-value to the selected pixel (P) using *step (c)*. According to many voxel space-rendering applications, statistically homogenous is measured with respect to computed values stored in pixels or with respect to depth factors associated therewith. (In this context "depth factors" relate to the distance from the eye to the position on the ray in which the ray casting was terminated, due to reaching the transparency value threshold or reaching the end of the voxel space.)
- 10 According to the preferred embodiment of the method of the present invention, a next position in *step (c)*, in the (transformed – see step (c) "SECONDLY") step-dependent series of positions along the vector, is selected using a variable step size from a present position; and the variable step size depends on an associated transparency for the transparency value of
- 15 the present position. For most applications the step size increases with the transparency. Nevertheless there may be applications wherein the visualization of the transparent portions of the transformed voxel space is the important aspect of the rendering.
- According to most embodiments of the present invention, the step size
- 20 from the present position to the next position is never greater than a voxel cross-section for the voxel space. This maintains that the ultimate visual quality of the image (being captured in the pixels of the virtual window for eventual display on a display device of media) will not be less than the spatial resolution of the voxel space.
- 25 According to another embodiment of the present invention, a first present position (of the transformed step-dependent series of positions) along the vector is at the pixel corresponding to the vector. This is equivalent to disregarding any portion of the voxel space that is between the vantage-point

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and the virtual window. According to the preferred embodiment, the first present position is at the eye (vantage point).

According to the preferred embodiment of the present invention, every next position (of the transformed step-dependent series of positions) is tested  
5 such that IF a (interpolated) voxel-value class iso-surface (as heretofore defined) has been detected along the vector between the next position and the present position, by virtue of the indication that the transparency value of the next position is smaller than that of the present position, THEN at least one position between the present and next positions is examined to provide a  
10 higher spatial resolution positioning for the iso-surface. For example in the series of position on the cast ray in Figure 3, positions (11) and (12) are on opposite sides of an iso-surface (13). If the computed visualization value for position (12) is greater than that computed at position (11) then the front facing portion of the iso-surface has been traversed by the cast ray. This  
15 constitutes the detection of a class iso-surface.

Proceeding (for example with a search) back to test a position (14) and forward to a position (15) will increase the precision of the contribution by the iso-surface to the visualization value. Stated more formally, between  
firstly the at least one position and secondly either the present or next  
20 positions, a further at least one position is examined to provide a higher spatial resolution positioning for the iso-surface. Furthermore, further examinations of positions are performed until a predetermined precision is achieved in locating the detected iso-surface.

According to an alternate embodiment of the present invention, every  
25 next position (of the transformed step-dependent series of positions) is tested such that IF a class iso-surface has been detected along the vector between the next position and the present position, by virtue of the indication that the transparency value of the next position is smaller than that of the present

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position, THEN a position between the present and next positions is assigned as the location for the detected iso-surface.

Another optional enhancement which is applied to embodiments wherein iso-surfaces are detected relates to a visualization-value for the detected iso-surface being applied to the vector's associated pixel (by finding a normal (25) to the iso-surface (26) at the vector intersection point or equivalently) using a contiguous gradient to the vector iso-surface intersection location or from proximate elements of the intersection. This is applied by calculating a current surface lighting contribution to the cumulative visualization-value, and accumulating this surface lighting visualization-value into the pixel. The surface lighting contribution is the visualization-value at the intersection position multiplied by the cosine of the angle (27) formed by the vector and the normal to the iso-surface at that location (28); and multiplying that by the cumulative transparency (accumulated in the associated pixel) squared.

According to the preferred embodiment of the present invention, an interpolated voxel value is calculated for a position along the vector from proximate voxels: using cubic interpolation for a position close to the vantage-point, or using linear interpolation for a position far from the vantage-point, or using a distance dependent graded mixture of cubic and linear interpolation for a position of a predetermined intermediate distance from the vantage-point. This is the preferred embodiment since the calculations are simple, the results are smooth and visually continuous, and the weighting of algorithmic efforts is high precision for close positions to the eye with a smooth decrease of precision as the position is further from the eye. Equivalently, any interpolation function, which traverses smoothly from high order precision for close positions to lower order precision for more distant position, is acceptable.

It should be appreciated that transparency values are unit normalized ("specific transparency"). In other words, the transparency values at each location denote the transparency corresponding to a "slab" of unit thickness. Usually the step size is not of a unit length. Therefore to calculate the  
5 transparency for the volume traversed by this step (interval), the unit normalized transparency value is exponentiated by the actual step size. Accumulating a transparency value into a pixel is by: multiplying the transparency value of the pixel by the transparency value for the interval. According to the present invention, the predetermined selection rule of  
10 accumulating in step (c) includes a front surface detection and a surface-lighting. Furthermore, according to the preferred embodiment of the present invention, selecting a next position in the step dependent series of positions is coordinated with an opacification process.

15 According to the preferred embodiment of the present invention, class iso-surfaces are opacified to facilitate a higher probability of detection. (Turning to Figure 4, which is a schematic diagram of a ray cast near an opacified iso-surface.) The opacification is performed by stretching the intervals defining the classes, where the more opaque classes take precedence.  
20 This has the effect that the iso-surfaces are shifted (inflated) from their actual location outward (to enclose less opaque regions). Iso-surfaces (16) has been opacified into expanded surface "buffers" bounded by iso-surface (17). On the cast ray (6), steps (20), (21) and (22) occur at regular intervals along the ray. At position (22) an opacity increase is detected because of the  
25 opacification. Therefore, the step size to (23) is reduced and the actual class iso-surface (16) is more likely to be detected. If the opacification were not performed, then the step after (22) would be at position (23A). Since position (23A) is in a region of transparency like that of position (21), the iso-surface would not have been detected without the opacification.

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According to another embodiment of the present invention, the predetermined selection rule of accumulating in step (c) includes a volume-lighting (see Figure 5).

5 According to further embodiments of the present invention, implementation of the method will be accomplished in parallel. According to one embodiment, step (c) is executed in parallel, by processing for the "each ray-cast vector of any more than one ray-cast vectors requiring the processing of step (c). This may result in allocating a processor (for effecting the  
10 algorithm of step (c)) to each cast ray. According to another embodiment, step (d) is executed in parallel; by processing for the each ray-cast vector of any more than one ray-cast vectors requiring the processing of step (d). Likewise, this may result in allocating a processor (for effecting the algorithm of step (d)) to each cast ray.

15 According to the preferred embodiment of the present invention, in step (d), "selecting" of pixels is ordered for progressively generating nested levels of resolution at the virtual window. This selecting may be as described in Figure 2, or in quad-tree fashion, or by simulated zoom (or pan), or the like.

According to the preferred embodiment of the present invention, each  
20 transparency value is associated with a visualization-value for representation on a graphics display device. Furthermore, the representation is for associated color or gray levels.

In general the present invention is amenable for adaptation to numerous geometric permutations. According to the preferred embodiment of  
25 the present invention, a center surface region of the virtual window is placed perpendicular to an orientation vector from the vantage-point; and the orientation vector is an average of the plurality of vectors. Furthermore, the virtual window is planar. Alternately, the virtual window is curved or warped. Likewise the pixels are preferentially arranged in the virtual window as a

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uniformly spaced rectangular grid. However alternatively, the pixels are arranged in the virtual window using circular coordinates, elliptic coordinates, or another conic projection of coordinates.

The method of the present invention, according to the preferred and  
 5 the basic embodiments is directed to rendering the voxel space contains data derived from a Computer Tomographic (CT) scan, Magnetic Resonance Image (MRI), an ultrasound scan, a Nuclear Magnetic Resonance (NMR) scan, a geophysical survey, a meteorological survey, a scientific simulation, an animation from a model having more than two dimensions, or a set of  
 10 simultaneous equations.

Accordingly, in the preferred embodiment of the present invention, the virtual window; having calculated, interpolated, or accumulated visualization-values stored in the pixels thereof; is rendered onto a display device.

15 (Turning now to Figure 5 which is a flowchart summarizing the basic logic process of the present method.) The follow notes are helpful in further understanding the detailed implementation of the present invention:

- ♦ "pass" denotes the iteration "phase", as measured from sparsely cast rays to higher resolution ray casting (or interpolation in the virtual  
 20 window) to complete filling of the virtual window (as in step (d)) - (also see Figure 2).
- ♦ "pixel" denotes one or more data storage "values" corresponding to a location or region of the virtual window.
- ♦ "CT" denotes cumulative transparency.
- 25 ♦ "(R, G, B)" denotes the red, green, and blue components of the visualization value.
- ♦ "T" denotes transparency value.
- ♦ "X += Y" denotes X is replaced with X+Y.
- ♦ "X \*= Y" denotes X is replaced with X\*Y.

The method of the present invention has been described with a certain degree of particularity with regard to ordering of steps, sub-steps, conditions, equivalents, and the like. This degree of particularity is not intended to limit  
5 the scope or spirit of the present invention, and is presented only for the purpose of conveying to those versed in the art such information as is necessary to properly appreciate the present invention and enabled embodiments thereof.

10 The present invention also relates to a computer system for forming a perspective rendering from a voxel space. (Turning now to Figure 6 which is a schematic diagram of a computer system for forming a perspective rendering from a voxel space.) This system includes:

- 15     ▪ a first memory media (61) wherein a voxel space is stored or represented;
- a computer processor (62) having data communications with the first memory media and with a second memory media, and the processor forms a virtual window of visualization pixels from a ray-casting into the voxel space, wherein the forming is according to the method for forming a high  
20     spatial resolution perspective rendering from a low spatial resolution voxel space, substantially as herein-before defined and illustrated; and
- the second memory media (63) wherein the virtual window of visualization pixels is stored or represented.

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The preferred embodiment of the present invention also relates to generating an index mapping of the homogeneity of the voxel space and to consulting this index mapping in order to decide if an interpolation computation is required – as part of the process of interpolating values of proximate voxels (step “c” *FIRSTLY*). For example, in order to further speed-up the process of ray-casting (with no penalty in image quality), an additional data-type is used, referred to as a BIT-VOLUME. In this data-type there is a single bit corresponding to each voxel. There are two variations in which a bit-volume may be used to facilitate ray-casting:

- 10 1<sup>st</sup> variation – Per class definition, the bit-volume is prepared (once) so that a value of 1 to a bit indicates the fact the a 4x4x4 cube of voxels (beginning with the voxel corresponding to that bit and extending to the positive sides of the x, y and z axes) belong to a single class.

During ray-case, when reaching a new position along the ray, the coordinates of the 4x4x4 cube of voxels needed for the cubic-interpolation of this position is calculated. Then, the value of the bit in the bit-volume corresponding to this cube (denoted by x) is queried.

a If  $x = 0$  then the interpolation (cubic or linear, depending on the distance from the eye as detailed above) proceeds as usual.

20 b Else (if  $x = 1$ ) then

- i. If the previous position (the interpolated value of which was sought) also had  $x = 1$ , then the previously found interpolated value is also taken as the current interpolated value.

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- ii. Else (if the previous position had  $x = 0$ ), the value of the interpolation is taken as an SINGLE voxel in the 4x4x4 cube of voxels.

Note that the interpolated value will be wrong. To see why this procedure works properly observe that for the algorithm to work properly (when visualization value is constant per class) it is sufficient for the used interpolated value to belong to the correct CLASS. Its exact value is inconsequential.

A sufficient condition that is easily met for which this correct-class-property holds in the above-described procedure is that the interpolated value always lies between the smallest and largest value used as input for the interpolation. Since a class is defined by an interval, and if all the inputs to the interpolation belong to the interval, then an interpolated value lying between the smallest and largest inputs must also belong to the interval and thus belong to the same class.

2<sup>nd</sup> variation – being similar in concept to the 1<sup>st</sup> variation – Per class definition, the bit-volume is initialized so that all bits are 0. In a similar fashion to the first variation, a value of 1 to a bit indicates that the 4x4x4 cube of voxels corresponding to that bit is known to belong to a single class. A value of 0 indicates that the class situation in the 4x4x4 cube is unknown or that they do not belong to a single class. Since at first nothing is known, the bit-volume is initialized to a constant 0.

During ray-cast, when reaching a new position along the ray, the coordinates of the 4x4x4 cube of voxels needed for the cubic-interpolation

of this position is calculated. Then, the value of the bit in the bit-volume corresponding to this cube (denoted by  $x$ ) is queried.

- a. If  $x = 0$  then the interpolation (cubic or linear, depending on the distance from the eye as detailed above) proceeds as usual. If a cubic interpolation is performed, then the appropriate  $4 \times 4 \times 4$  cube of voxels used for the interpolation are checked and if found to belong to a single class, the corresponding bit in the bit-volume is set to 1. Note that since these voxels are used in the interpolation anyway, this check does not imply a big overhead.
- b. If  $x = 1$  then the algorithm proceeds exactly as in way 1.

## CLAIMS

1. A method of forming a high spatial resolution perspective rendering from a low spatial resolution voxel data set, comprising:

5 (a) raycasting at least one ray from a predetermined location into the voxel space, by sampling points along said ray in a space defined by said voxel data set;

(b) accumulating the effect of opacity along the ray path, using opacity values at said sampling points, into a ray storage value;

10 (c) associating points along the cast ray with material classes, each material class of a plurality of possible material classes being associated with a set of opacity values;

(d) determining if a ray passes from a point in a first material class to a point in a second material class, using on the opacity values of the points;

(e) providing at least one association of a boundary visualization value with a boundary between two different material classes;

15 (f) if the ray is determined to pass between classes, accumulating a boundary visualization-value associated with a boundary between the two classes into said ray storage value; and

(g) repeating at least (a), (b), (d), and (f) for a plurality of cast rays; and

20 (h) forming a high spatial resolution perspective rendering from said determining ray storage values.

2. A method according to claim 1, comprising determining the location of said boundary in (f) during said ray casting.

25 3. A method according to claim 2, wherein said boundary is set to be at a position between said two points of different classes.

4. A method according to claim 2, wherein said boundary is determining by examining at least one addition sampling point between the two points of different classes.

30 5. A method according to claim 4, comprising repeating examining sampling points between points of different classes, until a desired precision of boundary determination is achieved.

6. A method according to any of claims 1-5, comprising calculating said boundary visualization value during said ray casting.

7. A method according to claim 6, wherein determining a boundary visualization value  
5 comprises determining a normal to said boundary at said point.

8. A method according to any of claims 1-6, comprising:  
providing an index array indicating for at least some of said voxels if a class-boundary  
does not pass near the voxel.

9. A method according to claim 8, comprising:  
avoiding said determining in (d) if a sampled point has a negative indication in said  
index array.

10. A method according to claim 8, comprising:  
reusing an opacity value from a previous sampled point a sampled point has a negative  
indication in said index array.

11. A method according to claim 8, wherein said index array is generated by setting a value  
20 indicating a lack of a boundary for all voxels that are surrounded by voxels in a same class.

12. A method according to any of claims 1-11, wherein said associated boundary  
visualization value comprises a surface lighting calculation of said boundary.

13. A method according to any of claims 1-12, comprising stopping said ray casting if said  
25 accumulated opacity is over a threshold.

14. A method according to any of claims 1-13, wherein said sampling points are separated  
by a step size and wherein said step size is dependent on the opacity value at the sampling  
30 points.

15. A method according to claim 14, wherein said step size is always smaller than a voxel  
cross-section along the path of the cast ray.

16. A method according to claim 14, wherein said step size is dependent on a opacity at a currently sampled point.

17. A method according to claim 14, wherein said step size is dependent on the opacities of  
5 neighboring voxels to the currently sampled point.

18. A method according to any of claims 1-17, comprising providing a definition of voxel value intervals for each class, prior to said ray casting.

10 19. A method according to any of claims 1-18, comprising:  
interpolating between voxels near said point; and  
transforming said interpolated voxel value into an opacity value for said point.

15 20. A method according to claim 19, wherein said interpolation is dependent on a distance  
between said sampled point and said vantage point.

21. A method according to claim 20, wherein said interpolation varies between a cubic interpolation for nearby points and a linear interpolation for far points.

20 22. A method according to any of claims 1-21, wherein said predetermining location is  
within the voxel space.

23. A method according to any of claims 1-22, wherein said voxel data set comprises a  
medical imaging data set.

25 24. A method according to any of claims 1-23, wherein (g) comprises:  
sparely casting rays; and  
determining if to cast at least one additional ray between cast rays.

30 25. A method according to claim 24, wherein determining if to cast said at least one  
additional ray comprises determining if said neighboring rays to said additional ray have  
statistically homogeneous ray storage values.



26. A method according to claim 25, wherein statistical homogeneity is determined with respect to the ray storage values.

27. A method according to claim 25 or claim 26, wherein statistical homogeneity is determined with respect to depth factors associated with the ray.

28. A method according to any of claims 1-27, wherein (h) comprises interpolating between stored values of cast rays.

29. A method according to any of claims 1-27, wherein (g) comprises progressively increasing the density of raycasting.

30. A method according to claim 29, wherein the progressively cast rays are cast in parallel.

31. A method according to claim 29, wherein additional cast rays are cast to progressively generate nested levels of resolution in the formed image.

32. A method according to any of claims 1-31, comprising rendering said formed perspective rendering on a display.

33. A method according to any of claims 1-32, comprising defining a window in or near the voxel space through which to cast said rays.

34. A method according to claim 33, wherein said window is perpendicular to a provided orientation vector.

35. A method according to claim 33 or claim 34, wherein said window is flat and rectangular.

36. A method according to claim 33 or claim 34, wherein said window is curved.

37. A method according to claim 33-36, wherein said window is defined by pixels in a uniformly spaced rectangular grid.

38. A method according to claim 33-36, wherein said window is defined by pixels using coordinates which are one of circular coordinates, elliptical coordinates and another conic projection of coordinates.

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39. A method according to any of claims 1-38, wherein said accumulation of opacity comprises updating a storage value CT as follows:  $CT = CT * T^{\text{step\_size}}$ , where T is a transparency value corresponding to the opacity value.

10 40. A method according to any of claims 1-39, wherein said rays are cast in parallel.

41. A method according to any of claims 1-40, wherein the voxel data set is generated by one of CT (Computerized Tomography), MRI (Magnetic Resonance Imaging), Ultrasound, a geophysical survey, a meteorological survey, a scientific simulation, an animation model  
15 having more than two dimensions and a set of simultaneous equations.

42. A method according to any of claims 1-41, wherein each voxel has associated therewith a visual representation value and comprising:

determining a visualization value associated with a sampled point from the voxel  
20 associated visual representation values; and  
accumulating said point associated visualization value into said stored value.

43. A method according to claim 42, wherein said visual representation value is a gray scale value.

25

44. A method according to claim 42, wherein said visual representation value is a color value.

45. A method according to any of claims 42-44, wherein accumulating said point  
30 associated visualization values comprises selectively accumulating values based on front surface detection.

46. A method according to any of claims 42-45, wherein said point associated visualization value comprises a volume lighting value.

47. A method according to any of claims 42-46, wherein said point associated visualization value comprises a surface lighting value.

5 48. A method according to any of claims 1-47, wherein advancing along a ray is coordinated with an opacification process.

49. Apparatus for forming a perspective rendering from a voxel space including:

(a) a memory for storing a voxel data set;

10 (b) a computer processor for applying the method of any of the claims 1-48 to said stored data set to form said perspective rendering; and

(c) a second memory for storing said formed perspective rendering.

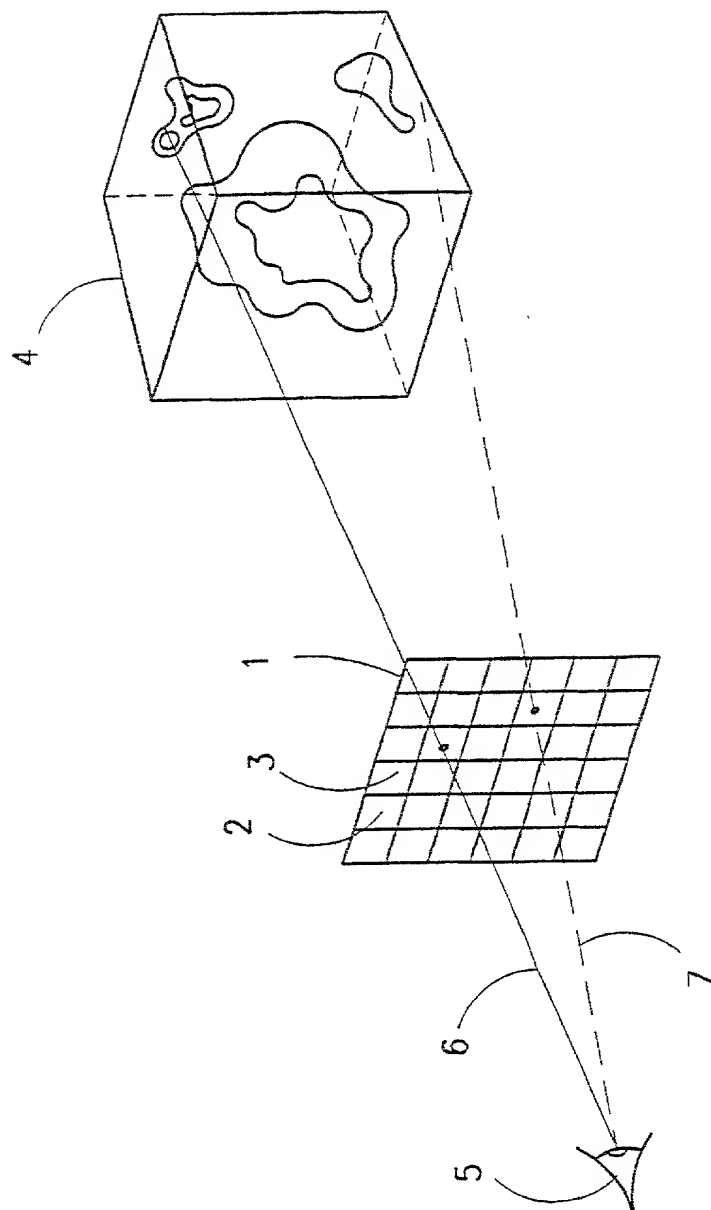


FIG. 1



FIG.3

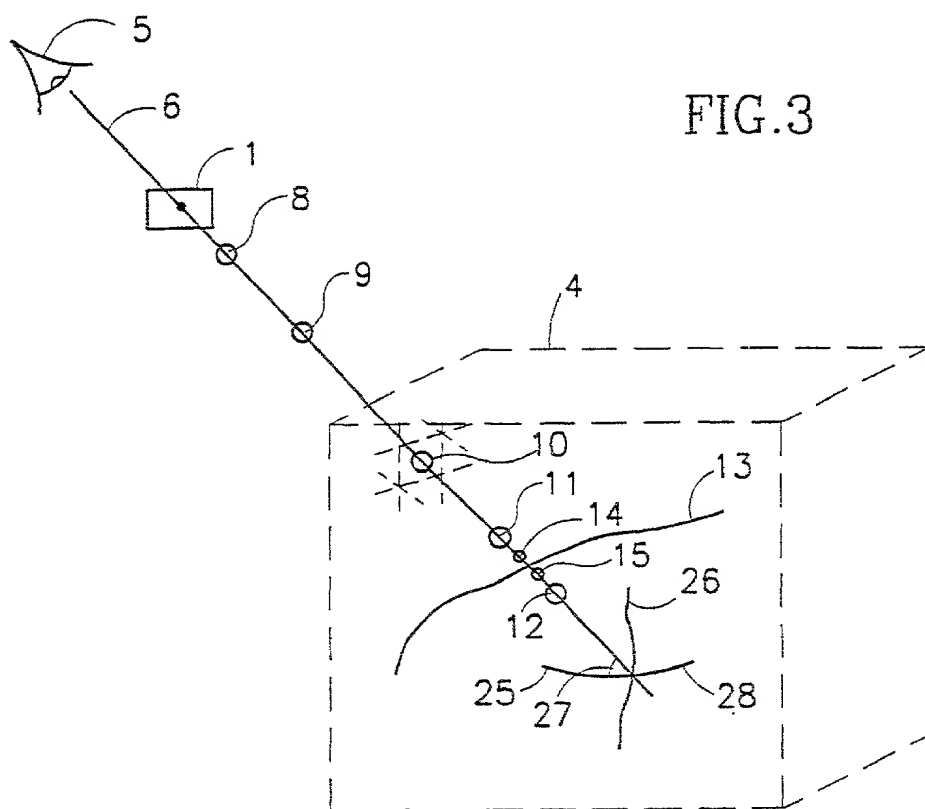
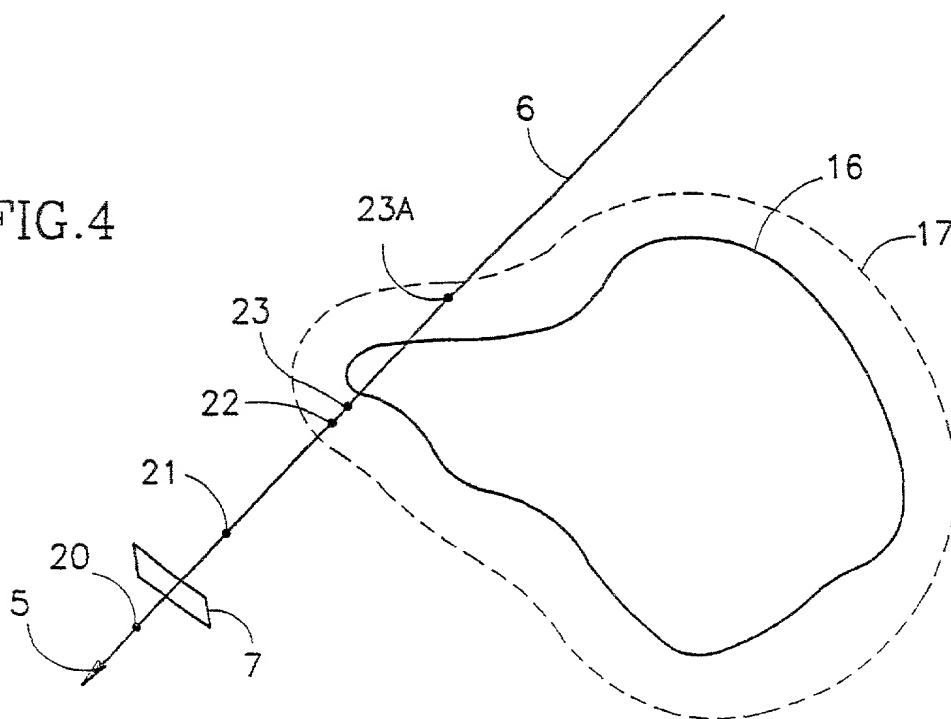
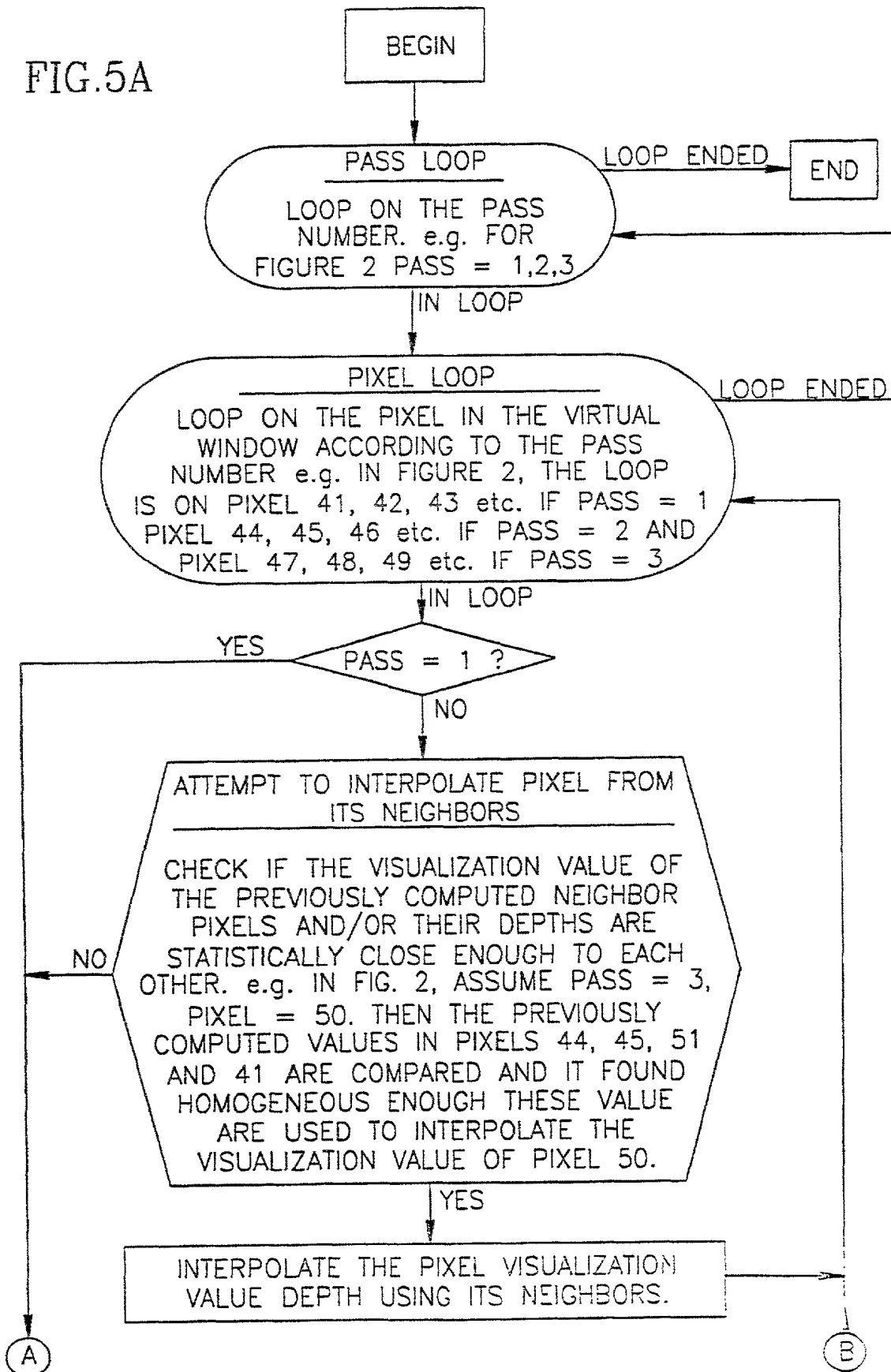


FIG.4



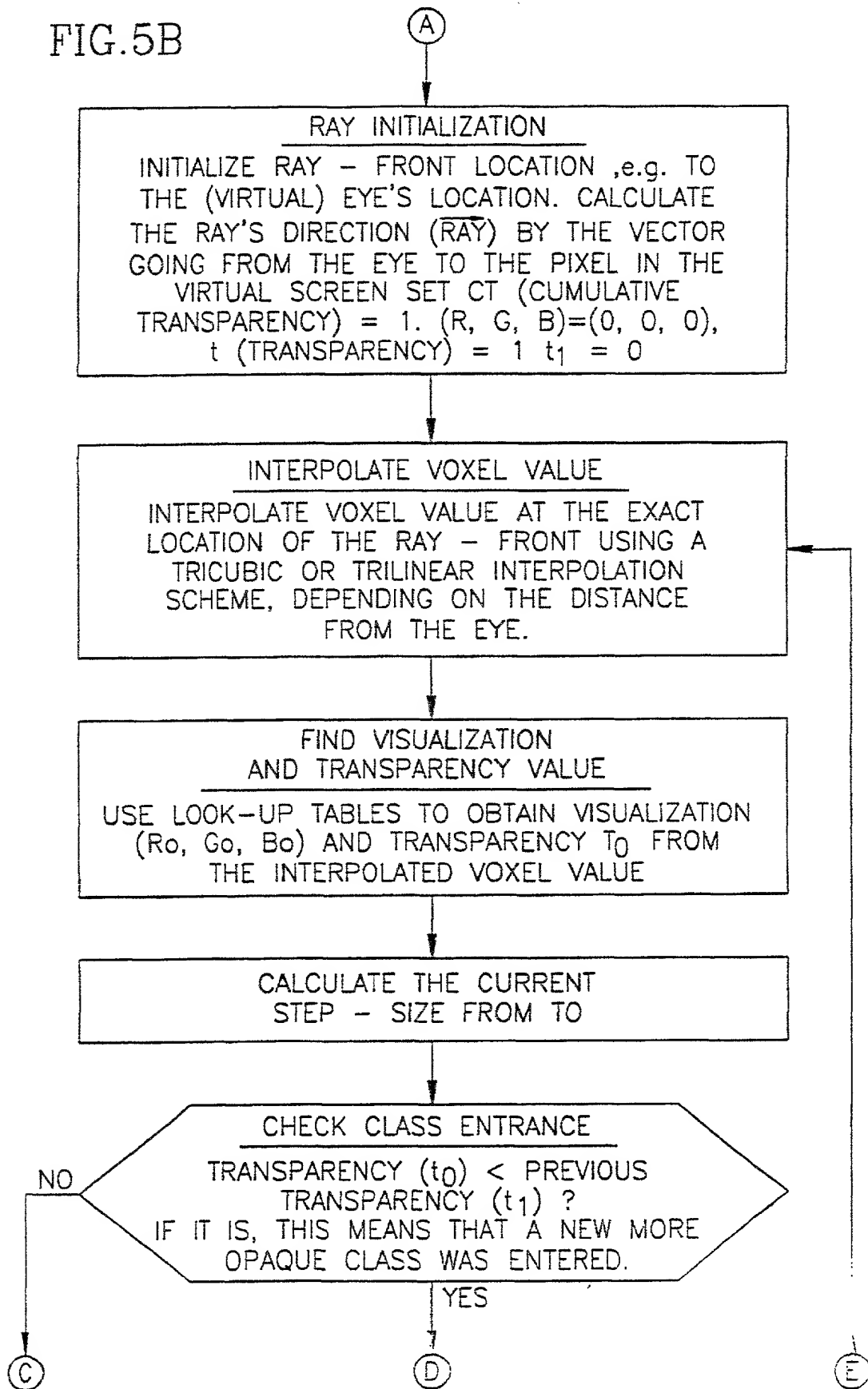
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FIG.5A



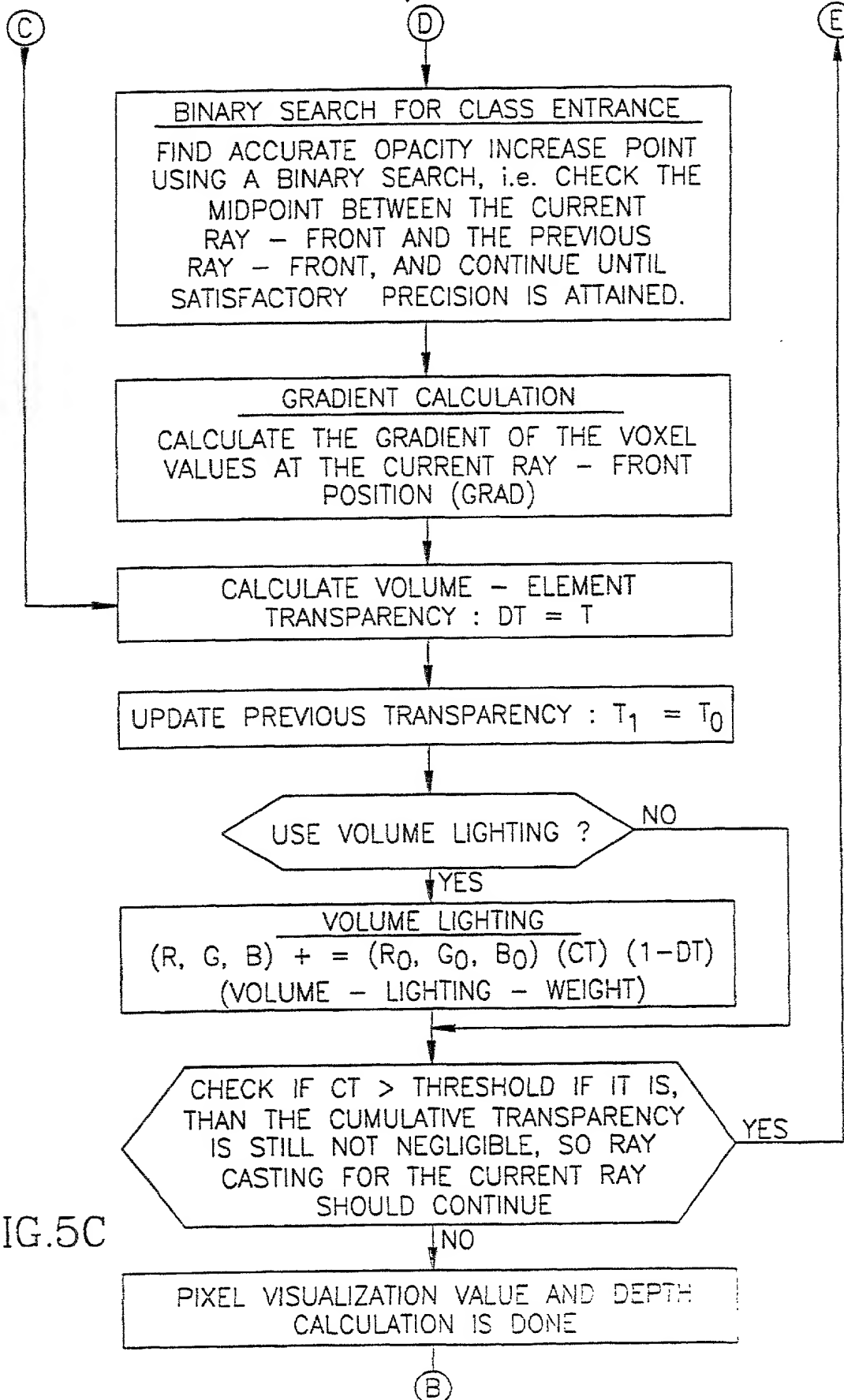
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FIG. 5B


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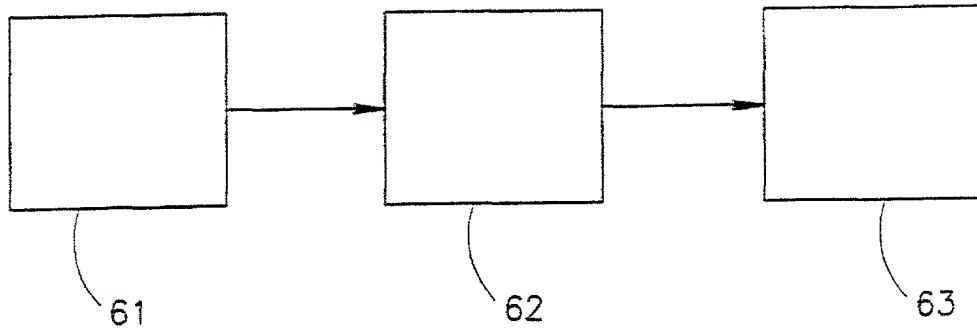


FIG.6

Docket No.  
032/02161

# Declaration and Power of Attorney For Patent Application

## English Language Declaration

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

### A METHOD FOR FORMING A PERSPECTIVE RENDERING FROM A VOXEL SPACE

the specification of which

(check one)

☐ is attached hereto.

☒ was filed on November 26, 1999 as United States Application No. or PCT International Application Number PCT/IL99/00639

and was amended ~~on~~ as in the annexes to the International Preliminary Examination Report  
(if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose to the United States Patent and Trademark Office all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d) or Section 365(b) of any foreign application(s) for patent or inventor's certificate, or Section 365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate or PCT International application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)			Priority Not Claimed
<u>127314</u>	<u>Israel</u>	<u>27 November 1998</u>	<input type="checkbox"/>
(Number)	(Country)	(Day/Month/Year Filed)	
<u>                    </u>	<u>                    </u>	<u>                    </u>	<input type="checkbox"/>
(Number)	(Country)	(Day/Month/Year Filed)	
<u>                    </u>	<u>                    </u>	<u>                    </u>	<input type="checkbox"/>
(Number)	(Country)	(Day/Month/Year Filed)	

I hereby claim the benefit under 35 U.S.C. Section 119(e) of any United States provisional application(s) listed below:

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

I hereby claim the benefit under 35 U. S. C. Section 120 of any United States application(s), or Section 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. Section 112, I acknowledge the duty to disclose to the United States Patent and Trademark Office all information known to me to be material to patentability as defined in Title 37, C. F. R., Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application:

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

\_\_\_\_\_  
(Status)  
(patented, pending, abandoned)

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

\_\_\_\_\_  
(Status)  
(patented, pending, abandoned)

\_\_\_\_\_  
(Application Serial No.)

\_\_\_\_\_  
(Filing Date)

\_\_\_\_\_  
(Status)  
(patented, pending, abandoned)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. (list name and registration number)

Paul Fenster, Reg. No. 33,877

Maier Fenster, Reg. No. 41,016

Phillip A. Weiss, Reg. No. 19,863

Yaakov Schatz, Reg. No. 44,320

William H. Dippert Reg. No. 26,723

Michael I. Wolfson, Reg. No. 24,750

R. Lewis Gable, Reg. No. 22,479

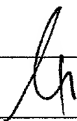
Send Correspondence to: William H. Dippert, Esq.  
Cowan, Liebowitz & Latman, P.C.  
1133 Avenue of the Americas  
New York, NY 10036-6799

Direct Telephone Calls to: (name and telephone number)  
William H. Dippert (212) 790-9200

Full name of sole or first inventor

Shmuel AKERMAN

Sole or first inventor's signature



2 May 01

Date

Residence

34 Sheshet Hayamim Street, Binyamina 30500, Israel ILX

Citizenship

Israel

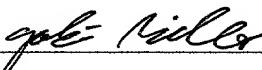
Post Office Address

34 Sheshet Hayamim Street, Binyamina 30500, Israel

Full name of second inventor, if any

Gad MILLER

Second inventor's signature



Date

2 May 2001

Residence

6 Rosenbaum Street, Tel-Aviv 64079, Israel ILX

Citizenship

Israel

Post Office Address

6 Rosenbaum Street, Tel-Aviv 64079, Israel